2011-09

Alternatives impact in combatant-ship design

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MONTEREY, CALIFORNIA

THESIS

**ALTERNATIVES IMPACT IN COMBATANT–
SHIP DESIGN**

by

Gerardo D. Sanabria Gaitan

September 2011

Thesis Advisor: Fotis Papoulias
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REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.			
1. AGENCY USE ONLY ***(Leave blank)***	**2. REPORT DATE** September 2011	**3. REPORT TYPE AND DATES COVERED** Master's Thesis	
4. TITLE AND SUBTITLE Alternatives Impact in Combatant-Ship Design			**5. FUNDING NUMBERS**
6. AUTHOR(S) Gerardo D. Sanabria Gaitan			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.IRB Protocol number ______N.A.__________.			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited			**12b. DISTRIBUTION CODE** A

13. ABSTRACT (maximum 200words)

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Once the mission capabilities that a ship must accomplish have been identified, a set of ship designs is created using a synthesis model, which is then formed into a multidimensional design space. Mission-effectiveness models are then used to simulate how well specific mission are accomplished in realistic warfighting scenarios.

The ship design space and each mission-effectiveness space are formed using response-surface designs created through a design of experiments methodology. The mission scenarios reside in a multiple-criteria decision space in which ship alternatives are assessed as solutions to the overall design problem. The combat-system design variables link the multiple response surfaces to form the relationships between mission capabilities and ship characteristics. A statistical analysis tool, JMP, creates a graphical environment that decision makers can use to interactively analyze different ship alternatives and determine the most effective design from a warfighting perspective.

The thesis demonstrates an example of selecting conceptual designs that meet desired mission-effectiveness criteria for medium-tonnage combatant ships engaged in mission scenarios of interest to the Colombian navy.

14. SUBJECT TERMS Conceptual Ship Design, Combatant Ship, Ship Trade Off Studies, Design Of Experiments, Design Space, Model Based Systems Engineering, Capability Based Design.			**15. NUMBER OF PAGES** 63
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540-01-280-5500 Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

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ALTERNATIVES IMPACT IN COMBATANT-SHIP DESIGN

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

and

MECHANICAL ENGINEER

from the

NAVAL POSTGRADUATE SCHOOL
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LIST OF ACRONYMS AND ABBREVIATIONS

COTECMAR	Science and Technology Corporation for Naval, Maritime and Riverine Industries” (acronym in Spanish)
DOE	Design of Experiments
ECM	Electronic Countermeasures
ESM	Electronic Support Measures
IFF	Identification, Friend or Foe
KPP	Key Performance Parameters
HM&E	Hull, Mechanical, and Electrical
MBSE	Model-Based Systems Engineering
MOE	Measure of Effectiveness
OPV	Offshore Patrol Vessel
PES	Surface Strategic Platform (in Spanish)
RSM	Response Surface Model
SAM	Surface–Air Missile
SSM	Surface–Surface Missile

Naval Architecture and Combat System Specific Symbols and Terms

B	Beam
C_P	Prismatic Coefficient
C_X	Maximum-transverse-section coefficient
GM/B	Transverse metacentric height to beam ratio (an indicator of stability)
hp	horsepower
kW	kilowatt
LWL	Load (or Design) Waterline
T	Draft
Δ	Displacement

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ACKNOWLEDGMENTS

I want to express my sincere gratitude to my thesis advisors, professors Fotis Papoulias and Clifford Whitcomb, for all their guidance, support, and patience in this research work; they encouraged me all the times in this difficult task and made it possible.

I wish to acknowledge the Colombian navy and the Science and Technology Corporation for the Naval, Maritime, and Riverine Industries for placing their trust in me and giving me the opportunity to achieve one of my personal and professional goals.

None of these efforts should be of any significance without the constant support and love of my parents, my wife, Mirsa, my son, David, my newborn daughter, Laura, and all my brothers and sisters; their voices of encouragement, their advice, and their hope in me were my constant guide through this wonderful experience.

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I. INTRODUCTION

A. BACKGROUND OF STUDY

According to the Colombian naval chief, a medium- and long- term objective of the Colombian navy is to design and build replacements for surface combatant ships currently in use. This task will be accomplished by the Science and Technology Corporation for Naval, Maritime, and Riverine Industries (COTECMAR) [1]. The new combatant ships will be designed to meet the requirements that allow the Colombian navy to maintain military capabilities that guarantee national security and defense.

There has been growing knowledge and experience in the Colombian shipyard in the construction of ships for military applications, as in the case of the riverine support vessel (“PAF”—the acronym in Spanish) and a new ocean patrol vessel (OPV) currently under construction; but the goal of designing and building a new combatant surface ship is a challenging project that will demand a careful process to achieve the highest effectiveness possible within constraints; especially in an environment where financial resources are always limited and combatant ships are increasingly expensive.

The implementation of effective methodologies that support decision making, especially in complex systems such as that represented by a combatant ship which must to able to perform multiple tasks is essential. This is especially true for decisions that are made in the early stages of the design process, and these decisions must achieve optimal design in the face of multiple criteria.

In the work done by Lieutenant Commander Jose Gomez [2], the focus was on the combat system design space and implementing methodology to identify the combat system combinations with the highest overall operational effectiveness. That methodology improved the design process, since once operational needs are set, identification of the physical architectures that best meets those needs from the point of view of the combat system can be identified. In this thesis, that methodology is expanded to include the integration of the physical architecture of the combat system into the

process of designing the combatant ship, so the best platform that can support an effective weapons system while simultaneously providing an optimal outcome with respect to operational capabilities, such as speed and endurance, can be determined.

Understanding the impact of different design variables such as hull characteristics, operational capabilities, and combat systems in the early stages of ship design will prevent, or at least reduce the risk of, design incompatibilities when the platform is assessed in terms of operational capabilities. Problems that lead to cost increases, reduced effectiveness, and delays can be identified in the beginning of the process in order to allow for timely corrections and to avoid stakeholder conflicts of interest in the advanced stages of the design process.

This work contributes to the development and implementation of methods and tools for assessment and decision making, which is one of the objectives proposed in [3] within the surface strategic platform ("PES"—the acronym in Spanish) project.

B. PURPOSE OF STUDY

This work explores some tools that should be used early in the conceptual design of naval ships, used as a basis for the study of a design space for new combatant ships. It also demonstrates the impact of different operational capabilities on overall design. This methodology enhances the process of developing tradeoffs between different system alternatives and improves their effectiveness in the multiple roles in which the ship will operate.

Identifying the mission capabilities a ship must accomplish is the first step in the design process. Next, a set of ship designs is created using the synthesis model, which is then used to form a multidimensional design space. Mission-effectiveness models simulate and predict how well each ship mission is accomplished, in order to predict overall effectiveness in the context of warfighting.

This thesis uses statistical methods to study the interaction of multiple variables representing operational capabilities in the ship-design process. The ship design space and mission-effectiveness spaces are formed using response-surface methods, created

through an experimental design methodology in which common design variables link the multiple response surfaces to form relationships between mission capabilities and ship characteristics. Using the statistical analysis tool JMP, a graphical and interactive environment is created that demonstrates the relationship between design alternatives, giving decision makers an interactive tool to analyze different ship alternatives and to determine the most effective from the perspective of operational capabilities.

C. BENEFITS OF STUDY

Integrating combat systems development and naval architecture into balanced ship design that is coupled to operational effectiveness—while considering top-level operational requirements—reduces risks that design outcomes will fail to meet desired military capability in the ship design process. These risks are mitigated by noting requirement conflicts before advanced stages in the ship design process, avoiding producing a design that will not meet operational requirements even though it may be a well-engineered ship design. The linkage between combat system effectiveness and naval architecture shows how changes in one variable will affect the overall design of the ship, making analysis of different tradeoffs between requirements and solutions possible.

D. SCOPE AND LIMITATIONS

The scope of this work is limited to demonstrating a basic methodology for early stage conceptual design of a medium-tonnage combatant ship. The purpose is to show the impact that different combat system have on the overall operational capabilities for the ship design, creating the design space and allowing feasible tradeoffs among the capabilities. This method enhances the analysis used for decision making in complex systems such as that represented by a multi-mission combatant ship, where multiple design variables interact at the same time, some with conflicting and non-commensurate measures.

According to preliminary studies done by [4], and taking as a reference existing multi-mission frigates or projects under construction (such as the Formidable class from Singapore, or Khareef class from Oman), the design space for the surface combatant for

this work will be in the range of 2500 tons and 3100 tons. This limitation sets constraints on the design problem and makes it more applicable for the Colombian navy.

The ship synthesis model considers only monohull vessels. The study of other hulls is not considered and could be a separate research topic. This assumption reduces the number of variables considered.

E. LITERATURE SURVEY

1. Introduction

Previous research has applied various tools and methods to the study of ship design and combat systems analysis in the context of operational capability and effectiveness. Use of a systems engineering approach and the implementation of design of experiments, among other theories and tools, is used in this study.

2. Systems Engineering Approach

This study uses a model-based systems engineering (MBSE) approach, in which the application of quantitative and qualitative models aid the design of the system [5]. The ship design process is by nature iterative, in which capabilities are identified and the design is refined as the concept develops. One of the keys to a successful outcome in ship design is the ability to make tradeoffs in the early stages to identify the most effective design in terms of operational capability.

Many studies have established the importance of bringing a systems engineering approach in the ship-design process, as in the work done by [9]. As stated by [6], systems engineering offers the best approach to building complex systems within the desired parameters of schedule, cost, performance, and quality. The intention of this work is not to introduce any specific process. There are several systems engineering process models in use today. The process approaches and steps used will depend on the nature of the system application and experience of the individuals on the team [7]. The method developed can be used with any of these systems engineering processes with the

additional characteristic that a continuous evaluation of the design can be accomplished to determine if the system is responsive to stakeholder needs.

3. Total Ship Systems Engineering

There is an increased need for new and more informed approaches to naval combatant ship design. As determined by [8], future ship development requires a greater amount of systems analysis that includes modeling and simulation. The analysis needs to support a continuous process of refining ship requirements, conducting tradeoff studies, and integrating methods to support analysis that will enhance ship integration and design.

Operational requirements are used in tradeoff studies to identify different configurations in the ship design space, to determine the most effective solution. Gaining an understanding of the requirements will produce a final design that meets customer needs. It gives the ability to specify the basic capabilities required of the ship. Proper definition of operational requirements is important since these dictate which aspects of a ship design can be adjusted while staying within the boundaries to the feasible design space.

The interaction between operational requirements and ship design is in many cases poorly established [10]. Yet, if the operational requirements do not account for important dependencies in design characteristics, the design process may lead to the wrong product. Unfortunately, the lack of a well-defined interaction between operational requirements and design models is common. Operations research systems analysis models have a strong focus on combat-system effectiveness, typically without taking into account the ways in which performance depends on the supporting engineering of the ship platform.

The tradeoff analysis to determine the interaction between variables in the ship design process, such as changes in the type or number of sensors or weapons and their impact on hull characteristics, will help naval architects determine which ship characteristics can be changed in order to gain the most effective ship from a mission

completion point of view. This reduces the risk of creating a final design solution in the early stages that is not useful against anticipated threats.

4. Generation of Alternatives

Developing system architecture is a creative process in which intuition and experience play an important role and past experience may be a reference in solving design problems. Combatant ship designs are analyzed in the context of analysis of alternatives, and are a response to the analysis of requirements and overall military effectiveness.

The work done by [2] states that as many different concepts as possible should be analyzed when designing a new system. This approach increases the possibility of achieving a product that improves upon previous versions. The development of architectural alternatives that satisfy stakeholder requirements is also required. According to [13], a system architecture depicts the summation of systems entities and capabilities that satisfies requirements and is consistent with the technical maturity and acceptable risks of available elements. Some other authors imply that there is no unique solution to satisfying user requirements and that system architecture is critical because it provides a framework for system development. This emphasizes the need for a design method that allows for the definition of the non-dominated solution set, and reveals the trade-off among the multiple variables involved.

5. Design of Experiments

Design of experiments (DOE) is a technique used to model and reveal relationships between inputs (or factors) and outputs (or responses) [11]. This technique is an extension of the methods used to represent processes that identify key factors for improving a product or process of interest. This technique represents a change from costly trial-and-error practices to cost-effective, versatile, and interactive tools based on statistical methods.

The process involved in the design of experiments is as follows:

- Identify factors and responses.
- Compute design for maximum information from runs.
- Measure responses. Analyze which factors have a great impact on responses and which do not, by means of mathematical fit or with graphical tools like the prediction profiler.
- Eliminate response factors without impact for a more accurate prediction of the interaction between factors and responses.
- Use models to find best factor settings for responses that have minimal statistical variability, to predict system behavior.

This experimental tool helps allocate resources based on the most important aspects of system behavior, since it will be used to identify the key drivers in the design process.

6. Tradeoff Methodology

The concept design of naval combatants has traditionally being accomplished using heuristics, accumulated experience, and parametric data, making it difficult to define a design space and thus find optimal solutions. The rapid change in technology and reduction in economic resources in defense budgets only serves to increase the complexity and difficulty of ship design optimization [12].

An increasingly popular method for concept exploration is the response surface method (RSM) technique. RSM helps solve the challenge of design optimization by identifying the variables that have the greatest impact on design, which are then used to define the design space, conduct tradeoff studies, and facilitate better-informed decision making. The use of this method with statistical modeling tools for the exploration of a conceptual design yields an infinite number of possibilities in the variations among factors. This leads to a broader analysis of the impact of the change of factors (inputs) in the design characteristics (outputs), thus making it possible to explore more design variations and find those most responsive to design iterations.

In this work, JMP software by SAS is used as the tool to develop the design of experiments and perform the statistical analysis, including the implementation of the RSM. This JMP software also has the ability to display an interactive visualization of the design space in a multi-dimensional graphical form by means of tools like a prediction profiler and contour plot. These tools display the predicted response as one factor changes while the other remains constant, thus showing the interaction between factors and responses.

With the aid of contour plots, which are analogous to a "concept exploration" map, it is possible to distinguish regions of feasible and non-feasible design; these regions are created when the desired low and high limits for the responses are set. One of the main advantages of this tool is the ability to see simultaneously the relationships among multiple factors and responses, making explicit the multidimensionality of the problem.

This methodology, which can create and represent the design space within JMP, can be used to conduct an interactive tradeoff that will serve decision makers 1) as a reference for the analysis of different relationships among the factors considered in the design, 2) as a way to detect conflicting requirements or attributes, 3) as a tool to identify factors that have no great impact on overall design, so time is not wasted on their analysis, and 4) as a way conduct a more informed decision making evaluation.

F. METHODOLOGY

The following methodology is used in this thesis. First, identify the operational requirements and operational capabilities that the ship must have, building on the research done in [1] and [2]. Second, use a ship synthesis tool to develop ship concept models representing these requirements. Specific point designs are used to represent the high and low ends of the design space and a midpoint. Third, use JMP software to develop an DOE using RSM. This step allows us to represent the design space in a graphical and interactive form that is employed in the tradeoff studies among design factors.

Finally, link weapon-system effectiveness and basic aspects of naval architecture by means of common variables within the RSM to determine the relationships between them and explore the design space for a medium-tonnage combatant ship.

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II. ARCHITECTURAL ALTERNATIVES

A. INTRODUCTION

A system architecture describes the elements of a system and their interrelationships. The architecture model describes what a system does and how it does it and including mappings of the physical entities or elements that will accomplish the different operational activities, or tasks, and the functions that the system must accomplish. The functions to be accomplished by Colombian naval vessel are taken from previous work in [2] and [3]. The first presents a group of operational scenarios in which the combatant ship is involved with developing specific missions, and the second presents some operational capabilities of interest for the Colombian navy.

This chapter describes how the synthesis step of the system design (in this case, the conceptual design of a combatant ship) is performed. As stated by [14], system design requires both integration and iteration, invoking a process that requires synthesis, analysis, and evaluation. It is important that these processes be integrated and applied iteratively and continuously over the design of the system.

Variables with major impacts on overall shape characteristics are the coefficients of form; these play an important role in the calculations of areas, volumes, and stability. According to [15], based on regression and statistical data, the values for prismatic coefficient are close to 0.6 and the values for midship coefficient are around 0.8 in combatant ships. It is also stated that some percentage values for payload and volumes serve as a reference to determine if the models generated during ship designs are unrealistic or unbalanced.

B. SHIP SYNTHESIS MODEL

In this thesis, a ship synthesis tool is used to perform calculations in a broad sense regarding the principal architectural aspects of a combatant ship. This tool is not intended to perform a very detailed ship design or make any type of technical sketch of the designed ship or produce a table of offsets to reproduce a hull form. It simply gives us a

balanced set of hull characteristics, estimating weights by classifying them into their constructive groups and calculating a high level transverse stability factor. The set of outputs from the synthesis model gives us a gross idea of the type, size, and associated principal characteristics of the ship.

According to [16], molded dimensions describe the faired surface defined by the framing, while displacement dimensions, which describe the wetted surfaces, are useful in determining stability and performance characteristics. The principal dimensions of a ship are length, beam, depth, draft, and freeboard. These dimensions are all calculated by the ship synthesis model, and in some way affect specific quantities such as speed, seakeeping, and capacity for the intended use of the vessel.

The ship synthesis model used is based on weight estimations. It works like that in [17], which explains details about common methods for weight estimation of naval surface ships. In this process, we account for the given weight of specific payload systems or items, through parametric estimations. In reality, the process of weight estimation is also an interactive procedure, wherein improved weight information is substituted into an existing estimate so as to represent the current status of the design at periodic intervals in the process. The uncertainty of exact value for weight estimation and possible weight increases, including future updates of systems, is accounted for by weight margins. In the models developed in this work, this weight margin was fixed at ten percent.

The main inputs to this synthesis tool are some specific characteristics of the combat systems (sensors, weapons, ordnance, control and communication), which are considered in this work as a payload factor, and some operational characteristics (endurance, range, and speed, among others).

Since the inputs for the synthesis models could vary within infinite very large number of possibilities, including variations in the combat systems configuration and operational characteristics from a small, patrol ship to those of a destroyer, a very broad range of possibilities could be used set as the response for the design problem. To narrow the design space to one that best matches the needs of the Colombia navy, some

constraints were set to establish boundaries to the problem solution. Table 1 shows the operational capabilities the ship uses as requirements. Some of those requirements will change as the conceptual design tradeoffs are conducted as the design matures, since this analysis shows which aspects have a higher impact on ship design and can allow for the allocation of more resources and effort towards improving those aspects. Requirements will mature as the project advances.

Table 1. Ship operational requirements.

Characteristic	Requirement
Combat Information	Display of ASW AAW ASUW
Weapons Control System	Control over guns, missiles
Information Display	Optimum
Radar	For air/surface surveillance
Warfare Capabilities	ASW AAW ASUW
Communications	HF, VHF, UHF, Sat comm
Displacement	2,500-3,100 tons
Endurance speed	18 Knots
Sustained speed	30 Knots
Endurance	30 Days
Range	5,000 NM
Helicopter	Medium (probably AAV)

C. BASELINE SHIPS MODELS

As stated above, the Colombian navy ship must be a multi-mission (or multitask) combatant with operational capabilities for surface, submarine, electronic, and air warfare. To begin the process of creating a design space through construction of models of some alternatives of ship design, research was conducted on existing ships and projects under construction with operational capabilities between 2500 and 3100 tons. From this research, three configurations of combat systems were selected to characterize three ship to be synthesized in combination with other operational requirements (e.g., speed, range, endurance). Those configurations represent typical combat system configurations for high, low, and middle points in the design space.

The three models are used to offer a basis for existing designs that could be found in the planned design exploration space. They also show that the design space is a compromise among the various operational capabilities.

1. Base Model One

Base model one represents the high end of the design space: a ship with the largest number of weapons and sensors and highest level of operational requirements. The operational characteristics of this model are listed in Table 2.

The ship synthesis model was used considering a combined-diesel and diesel (CODAD) propulsion plant, as used by Colombian naval ships. The implementation of other propulsion systems, such as combined diesel and gas turbines (CODAG) will require a deeper study, taking into account all aspects of this kind of design change involving gas turbine propulsion systems. However, this ship synthesis tool could be used if gas turbines were considered by the Colombian navy.

Table 2. Model one operational characteristics.

CHARACTERISTIC	
Endurance	30 days
Range	4000 NM
Sustained Speed	30 Knots
SAM	16 (30 km) - 16(120 km)
SSM	8
Torpedoes	6 Light weight
Gun	76 mm
Radar	3D multi-function (250 km range)
Sonar	Hull mounted
Helicopter	Medium

Once the sensors, weapons, ordnance, and all the equipment considered as payload in a combatant ship are determined, the process of ship design synthesis can begin. Most of the payloads used in this design are currently used in existing combat and weapon systems (e.g., radar and missiles).

The final result of the model is shown in Table 3. An iterative process was conducted in order to design a balanced ship.

In this iterative process, we are only interested in general characteristics like weight, weight allocation, area, and electrical-power consumption, since our focus is on conceptual ship design.

Table 3. Model one synthesis model outputs

DESIGN SUMMARY					
Principal Characteristics			**Weight Summary**		
LWL	371.587	ft	Description	Weight (lton)	
Beam	46.922	ft	Group 1	1,074.364	
Depth, Station 10	30.000	ft	Group 2	334.863	
Draft	14.219	ft	Group 3	146.420	
GMT	5.464	ft	Group 4	113.548	
GM/B Ratio	0.116		Group 5	464.898	
CP	0.600		Group 6	248.150	
CX	0.720		Group 7	62.550	
			Sum 1 - 7	2,443.754	
Sustained Speed	30	knt	Design Margin	244.479	
Endurance Speed	18	knt	Lightship Weight	2,689.274	
Endurance	4000	nm	Loads	364.237	
			Full Load Weight	3,053.511	
Number Main Engines	4		Full Load KG	19.921	ft
Main Engine Rating	12071.5	hp			
			Military Payload	340.510	lton
SHP/Shaft	24143	hp	Payload Fraction	0.112	
Propeller Type	CRP		Fuel Weight	193.697	lton
Propeller Diameter	9.7103635	ft			
			Manning		
Number SSGTG	3		Officers	15	
SSGTG Rating	1000	kW	Enlisted (Including NCO)	86	
Maximum Margined Electrical Load	1740.0869	kW	Total	101	
Area Summary			Volume Summary		
Hull Area	18517.724	ft2	Hull Volume	194436.1	ft3
Superstructure Area	11428.571	ft2	Superstructure Volume	120000	ft3
Total Area	29946.295	ft2	Total Volume	314436.1	ft3

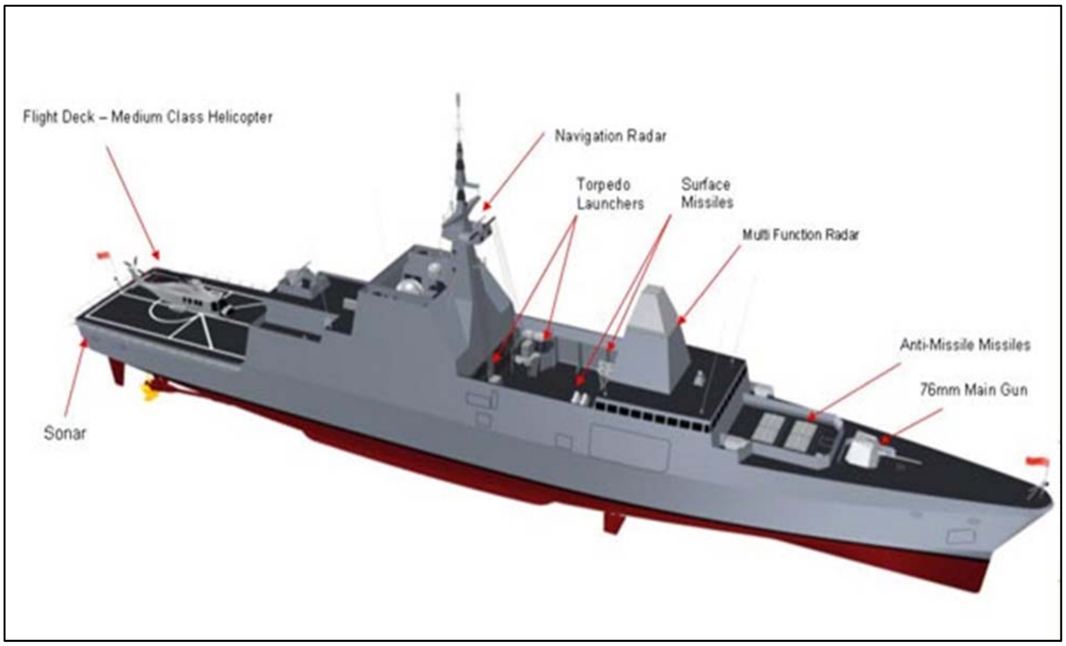

Figure 1. Reference ship for model one (From http://www.naval technology.com/projects.html)

2. Base Model Two

Base model two represents the lower end of the design space. It is a combatant with fewer sensors and weapons, with some other operational characteristics also reduced. Table 4 represents a summary of the most important operational characteristics affecting the synthesis model.

Table 4. Model two operational characteristics.

CHARACTERISTIC	
Endurance	30 days
Range	4,500 NM
Sustained Speed	25 Knots
SAM	12 (20 km)
SSM	8
Torpedoes	6 Lightweight
Gun	76 mm
Radar	3D multibeam
Sonar	Hull mounted
Helicopter	Medium

Table 5 shows the final results of the ship synthesis model. Lower payload weights yield a smaller ship with less displacement than the Model 1 version. Another important outcome in this model is reduction in sustained speed. The changes in various factors will allow exploring the impact of more factors in the conceptual design.

Table 5. Model two synthesis model outputs.

DESIGN SUMMARY					
Principal Characteristics			**Weight Summary**		
LWL	288.0	ft	Description	Weight (lton)	
Beam	44.4	ft	Group 1	773.8	
Depth, Station 10	28.0	ft	Group 2	234.6	
Draft	12.5	ft	Group 3	146.4	
GMT	4.7	ft	Group 4	83.7	
GM/B Ratio	0.106		Group 5	423.2	
CP	0.69		Group 6	238.2	
CX	0.8		Group 7	37.6	
			Sum 1 - 7	1936.5	
Sustained Speed	25.0	knt	Design Margin	193.8	
Endurance Speed	18.0	knt	Lightship Weight	2131.3	
Endurance	4500	nm	Loads	376.1	
			Full Load Weight	2507.4	
Number Main Engines	2		Full Load KG	18.74	ft
Main Engine Rating	13000	hp			
			Military Payload	273.6	lton
SHP/Shaft	13000	hp	Payload Fraction	0.11	
Propeller Type	CRP		Fuel Weight	213.7	lton
Propeller Diameter	8.2	ft			
			Manning		
Number SSGTG	3		Officers	15	
SSGTG Rating	1000	kW	Enlisted (Including NCO)	95	
Maximum Margined Electrical Load	1403	kW	Total	110	
Area Summary			Volume Summary		
Hull Area	15551	ft2	Hull Volume	163282	ft3
Superstructure Area	11429	ft2	Superstructure Volume	120000	ft3
Total Area	26979	ft2	Total Volume	283282	ft3

3. Base Model Three

This model represents an approximate midpoint for the design space. The payload is very similar to that in the above model, with some important differences considered in some operational characteristics. Table 6 shows the major operational characteristics of this model.

This third point design represents the region of the design space where a compromise optimal solution may lie and might make it possible to avoid having to use simply a linear solution that would result if only 2 extreme point designs are evaluated.

Table 6. Model three operational characteristics

CHARACTERISTIC	
Endurance	30 days
Range	4000 NM
Sustained Speed	32 Knots
SAM	8 (20 km)
SSM	8
Torpedoes	6 Light weight
Gun	5 in.
Radar	2D
Sonar	Hull mounted
Helicopter	Medium

Table 7. Ship synthesis model three output

DESIGN SUMMARY					
Principal Characteristics			Weight Summary		
				Weight	
LWL	386.5	ft	Description	(lton)	
Beam	42.2	ft	Group 1	949.1	
Depth, Station 10	28.0	ft	Group 2	335.9	
Draft	12.3	ft	Group 3	146.4	
GMT	3.7	ft	Group 4	99.9	
GM/B Ratio	0.087		Group 5	453.3	
CP	0.62		Group 6	254.4	
CX	0.8		Group 7	32.6	
			Sum 1 - 7	2270.6	
Sustained Speed	32.0	knt	Design Margin	227.2	
Endurance Speed	18.0	knt	Lightship Weight	2498.8	
Endurance	4000	nm	Loads	342.6	
			Full Load Weight	2841.3	
Number Main Engines	4		Full Load KG	17.78	ft
Main Engine Rating	12071.5	hp			
			Military Payload	277.2	lton
SHP/Shaft	24143	hp	Payload Fraction	0.10	
Propeller Type	CRP		Fuel Weight	177.7	lton
Propeller Diameter	9.0	ft			
			Manning		
Number SSGTG	3		Officers	15	
SSGTG Rating	1000	kW	Enlisted (Including NCO)	100	
Maximum Margined Electrical Load	1587	kW	Total	115	
Area Summary			Volume Summary		
Hull Area	16459	ft2	Hull Volume	172814	ft3
Superstructure Area	10476	ft2	Superstructure Volume	110000	ft3
Total Area	26935	ft2	Total Volume	282814	ft3

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III. COMBATANT SHIP DESIGN SPACE

A. DESIGN OF EXPERIMENTS

DOE is a statistical technique used to represent and establish the relationship of many possible variables (factors) on the process output (response). When considering multiple factor systems, this tool allows us to identify the effect on different responses when varying one factor while maintaining the others constant.

This technique is accompanied by graphical tools that show the tendency of the relationship between factors and responses interactively, thus showing which factors have the greater impact on responses (evaluating the slope of the tendency).This evaluation is developed keeping the amount of modeling and simulation to a minimum.

Once the factors with greater impact on responses are identified, it is beneficial to design another experiment with only those factors and consider them with a higher order, non-linear model. As revealed by [18], it is possible to develop a higher order model with the resulting data. The plot of that model is a three-dimensional surface that can be used to predict the effect of various factors on the responses. This model is called a response surface and makes it easy to visualize the relationship between factors and responses, develop tradeoffs between them, and facilitate better information in the interaction between factors and responses.

For this thesis study, the DOE and RSM are developed using the SAS JMP software, which provides graphical tools like a contour profiler and prediction profiler, as well as statistical data and Pareto plots that allow the analysis of relationships between factors and responses. These also allow designers and decision makers to explore the space for the conceptual design of a medium combatant ship to identify the factors with great impact on ship design. It is also allows the ability to conduct ship tradeoff studies based on operational capability, allowing ship-design configuration decisions concerning warfighting effectiveness over multiple missions, with explicit consideration of combat and weapon-system characteristics.

B. SELECTION OF FACTORS

Research on multi-mission combatant ships already built, or under construction, that exemplify the capabilities of interest to the Colombian navy was conducted. From these studies, the sensors, weapons, ordnance, equipment, systems for control and communications, and all the equipment and systems for helicopter-operations capability, were integrated as a group, using the weight, electric power, and center of gravity of these systems as the primary basis of their characterization, named "payload." This is the major input for the ship synthesis model and also the factor that best characterizes the capabilities of the ship, especially those of interest in the conceptual design, since they represent the ship solution space based on the operational requirements.

This study also determined which other parameters will be of interest in exploring the design space, such as length, beam, and draft, since they have an important place in the synthesis of a ship. This was done using the ship synthesis tool in an iterative process for obtaining a balanced model. From this process, it is possible to identify the key inputs in the effort of the design.

Four factors were used to characterize the ship design model: payload weight (which took into consideration all the aspects mentioned above), fuel capacity, range, and installed shaft horsepower. Since range is a factor that varies according to an operational scenario, engine type, specific fuel consumptions, etc., it is a very difficult variable to simulate. Thus, range is set as an input, with a desired value of 5000 NM and a lower limit of 4000 NM.

The responses of interest in this model are the principal dimensions of the ship (LWL, B, T), as well as the displacement, endurance speed, sustained speed, and stability factor (GM/B).

The set of factors and responses completely characterize a basic conceptual ship design, since it considers the weapon system and sensor configuration and, at the same time, provides a broad idea of the size and type of platform that will accommodate these systems and equipment.

In this case, given the four selected factors (all of them continuous), and considering second order interactions between factors, a custom design was developed, resulting in a model design with sixteen points, each representing a different combination of the four factors in a possible design. Table 8 contains the design points with the factors value for each point.

Table 8. Design of experiments for ship synthesis model.

	PAYLOAD WEIGHT	FUEL CAPACIT...	RANGE	SHP
1	350	170	4000	47000
2	270	125	5000	47000
3	270	170	5000	47000
4	270	170	4000	23500
5	350	125	4000	47000
6	270	125	5000	23500
7	350	170	5000	23500
8	350	125	4000	23500
9	350	125	5000	23500
10	350	125	5000	47000
11	350	170	5000	47000
12	270	125	4000	47000
13	350	170	4000	23500
14	270	170	4000	47000
15	270	125	4000	23500
16	270	170	5000	23500

C. RESULTS

For each of the sixteen points in the DOE, the ship synthesis tool was used to produce the ship design that meets the values of the factors as inputs for each point. These designs contain the values for the responses of interest in our DOE to complete the information required to crate the RSM using JMP. The sixteen points represent feasible designs that meet all requirements from the point of view of naval architecture, all of them balanced.

Table 9 shows the complete design of each of the sixteen points with the values for each factor and for each of the responses selected as being of interest in the analysis of the ship synthesis design space.

Table 9. DOE factor and responses.

	PAYLOAD WEIGHT	FUEL CAPACIT…	RANGE	SHP	DISPLACEMENT	LWL	BEAM	DRAFT	GM/B	SUSTAINED SPEED	ENDURANCE SPEED
1	350	170	4000	47000	3095	374	47	14.3	0.12	34	19.7
2	270	125	5000	47000	2875	391	42.1	12.3	0.09	33	16
3	270	170	5000	47000	2925	391	42.5	12.4	0.094	34	18.5
4	270	170	4000	23500	2510	288	44.4	12.5	0.106	25	19
5	350	125	4000	47000	3050	373.6	46.7	14.2	0.114	34	17.1
6	270	125	5000	23500	2475	288	44	12.4	0.101	25	16
7	350	170	5000	23500	2960	374	46	13.9	0.106	30	18
8	350	125	4000	23500	2890	374	45.5	13.8	0.096	30	17.5
9	350	125	5000	23500	2905	374	45.6	13.8	0.098	29	15.8
10	350	125	5000	47000	3075	374	46.9	14.2	0.117	33	15.5
11	350	170	5000	47000	3120	374	47.2	14.3	0.122	34	18
12	270	125	4000	47000	2860	391	42	12.3	0.086	34	18
13	350	170	4000	23500	2930	374	45.8	13.9	0.102	29	20.1
14	270	170	4000	47000	2900	391	42.3	12.4	0.091	33	20.4
15	270	125	4000	23500	2450	288	43.8	12.3	0.097	25	17
16	270	170	5000	23500	2540	288	44.6	12.5	0.11	25	17.7

Figure 2 shows the prediction profiler for this model. From this interactive and graphical tool, we can infer that the payload weight and installed horsepower factors have a great impact in all the responses, while the fuel capacity and range factors have little impact in almost all the responses, except in sustained speed.

The next step in refining the model is to analyze the effect of each factor in each of the responses, considering which are statistically significant. This process will be done using the statistical values of each response with respect to the factors. The factors that are not statistically significant are removed from the DOE and a new experiment is set. Table 10 represents the new DOE, in which the fuel-quantity factor and the endurance-speed response were eliminated because of two factors; first fuel quantity is a minor factor, and second, in almost all the points designed, the endurance speed is approximately 18 knots, so it is set at a mid-value of 18 knots.

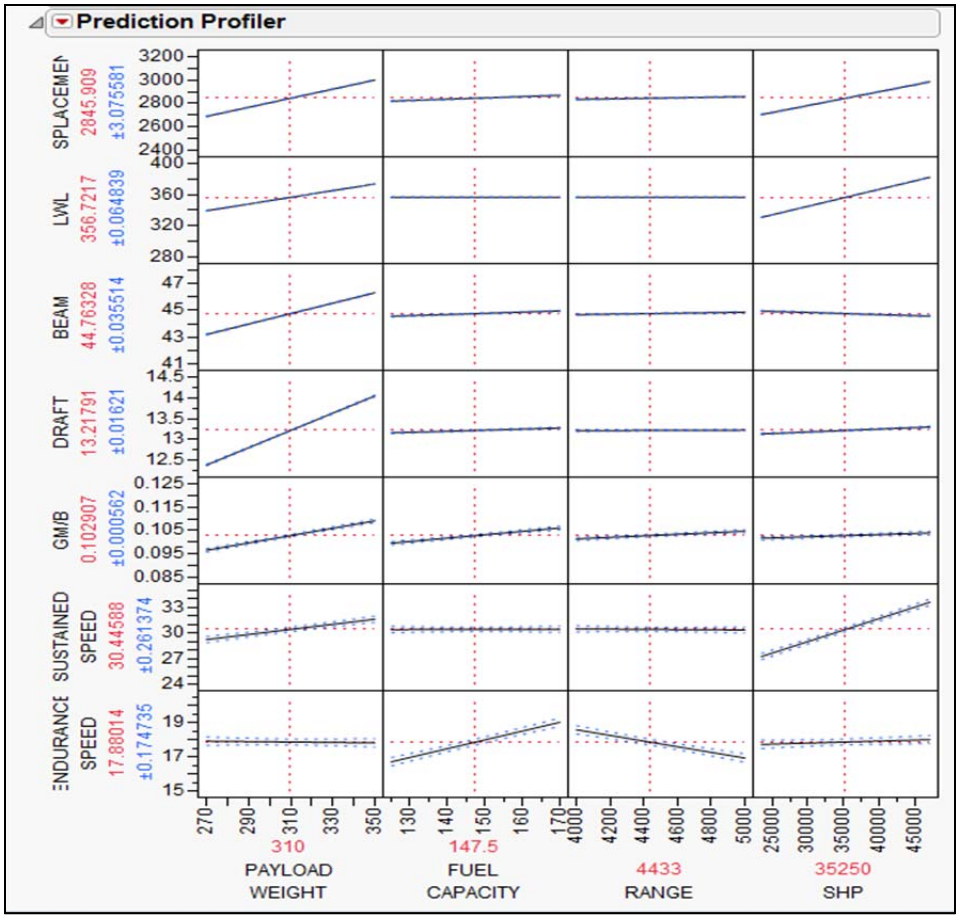

Figure 2. DOE ship synthesis model prediction profiler.

The next experiment also considers sixteen points, each representing a particular point design created using the ship synthesis model. In this new DOE, midpoint values are considered and a central composite design was performed. Table 10 presents the values of the factors (three for this new DOE) and six responses.

Table 10. Central composite design DOE.

	Pattern	PAYLOAD WEIGHT	RANGE	SHP	DISPLACEMENT	LWL	BEAM	DRAFT	SUSTAINED SPEED	GM/B
1	---	270	4000	23500	2475	288	44	12.4	25	0.101
2	a00	270	4500	35250	2700	340	44.3	12.7	30	0.098
3	-++	270	5000	47000	2910	391	42.4	12.4	32	0.093
4	000	310	4500	35250	2860	345	46.4	14.5	32	0.105
5	00A	310	4500	47000	2975	360	46.3	14.5	34	0.108
6	0a0	310	4000	35250	2855	355	45.7	14.3	32	0.099
7	+--	350	4000	23500	2895	374	45.5	13.8	29	0.097
8	++-	350	5000	23500	2960	374	46	13.9	29	0.106
9	+-+	350	4000	47000	3060	371.6	46.9	14.2	33	0.116
10	A00	350	4500	35250	3020	374	46.5	14.1	31	0.112
11	0A0	310	5000	35250	2960	358	47	14.2	32	0.115
12	+++	350	5000	47000	3125	374	47.3	14.3	33	0.122
13	-+-	270	5000	23500	2540	288	44.6	12.5	25	0.111
14	000	310	4500	35250	2860	345	46.4	14.5	32	0.105
15	--+	270	4000	47000	2850	391	41.9	12.3	32	0.09
16	00a	310	4500	23500	2730	320	47.8	14.3	29	0.102

Figure 3 shows the new DOE prediction profiler, which visualizes the great impact that payload weight and installed SHP have on the model, while range has a lower impact, though still important. It is also clear that the relationship between factors and responses is no longer linear.

This nonlinearity in the relationship of factors and responses demonstrates that in ship design, the tradeoffs between requirements are not as straightforward as we might desire, and will involve a compromise between desired requirements while maintaining the feasibility of possible solutions. This is the reason that tools like DOE, which allow a tradeoff analysis through a graphical and interactive methodology, enables better-informed decisions.

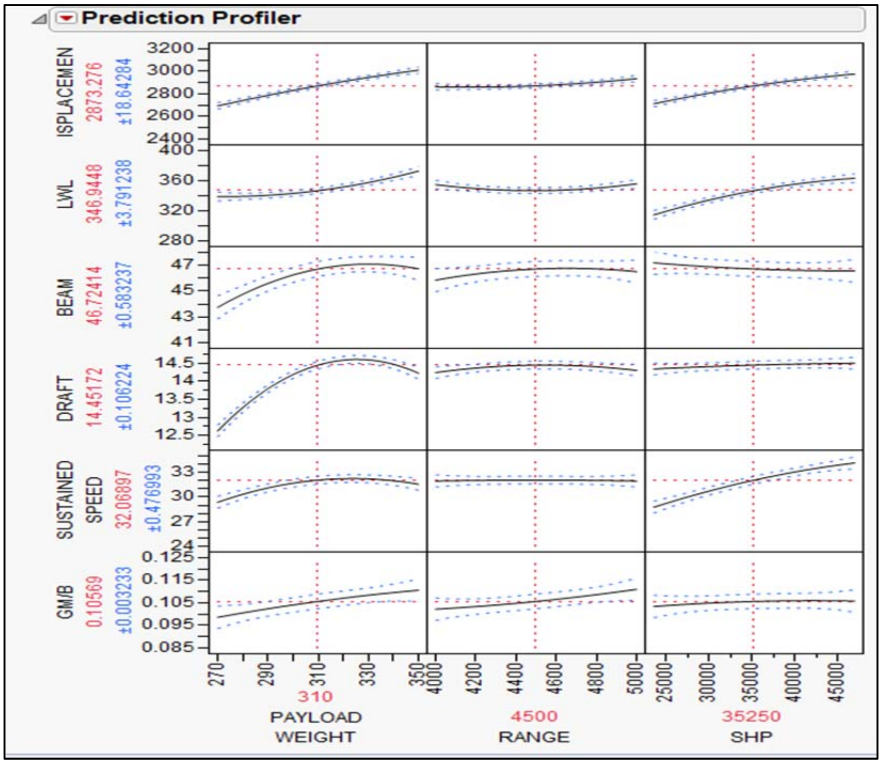

Figure 3. Central composite DOE

According to [19], the prediction profiler is a powerful tool for an analyst or a designer and useful for a decision maker. However, another practical tool with a graphical interface that presents actual response surfaces and is useful in tradeoffs studies is the contour plot, which is also available with JMP.

The contour plot is a visualization tool that can simultaneously show response surfaces with respect to two competing factors. In the case of ship design, from the prediction profiler, it is seen that the range factor has a very low impact in the responses; therefore the analysis can be done with more emphasis on payload weight and installed SHP.

With contour plots, the contour values for each response can be seen in relation to the factors considered as a map. These contours present regions for feasible and non-feasible designs with respect to the two factors considered.

The contour plot provides the possibility of setting desired boundaries for each response. Once the desired values of high and low limits are identified, the contour plot shows some regions as white (where tradeoff is feasible), and some as shadowed (where the design is not feasible). Figure 4 shows a contour plot for the ship design DOE.

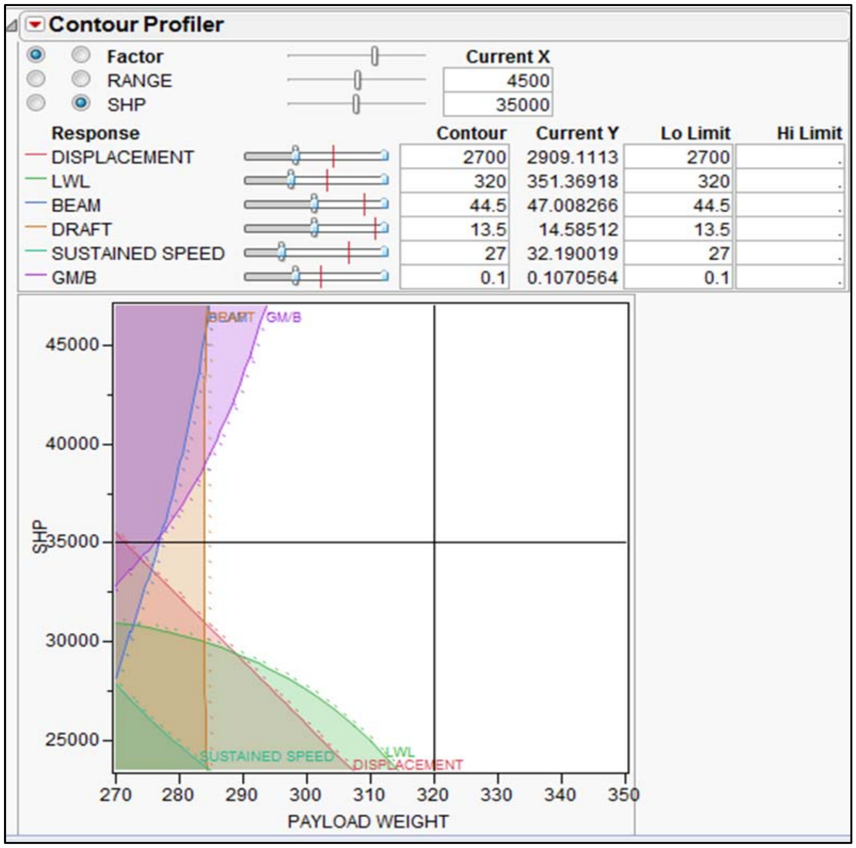

Figure 4. Contour profiler for ship synthesis DOE.

If a shaded area is achieved in the contour profiler, then a variation in the response thresholds must be developed to achieve a feasible design area – one that falls within the white region of the plot. Once the design space has been identified, it is possible to perform interactive tradeoff studies, and more information is available for the decision-making process. The interior and boundaries of the design space can be explored

by adjusting the thresholds of the surface contours. This gives a more exact idea of constraints and conflicting requirements in the design space, and allows better understanding of the requirements and their relationships, and contributes to more effective decision making.

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IV. LINKING SHIP SYNTHESIS MODELS AND COMBAT SYSTEM EFFECTIVENESS

A. INTRODUCTION

The purpose of a combatant ship design is not only to design a hull that can move at a certain speed or have enough volume to carry the different systems and elements necessary to perform missions; it also needs to be capable of facing and defeating probable threats. The previous chapters show a methodology to identify, build, and explore the design space that allows the performance of tradeoff studies. These studies in turn display the relationships among the factors and responses characterizing surface ship design. The objective of this chapter is to link the design of a multi-mission combatant ship with system mission effectiveness, to guarantee that the ship design will meet operational requirements and fulfill stakeholder expectations.

To this end, some tools and models used by [2] and [20] are used for reference. In the work done in [2], some models were developed to calculate the overall measure of effectiveness (OMOE) of the combat system and allow us to predict the OMOE of any combat system. In the work done by [20], a meta-model was used in the design of a patrol vessel to perform interdiction operations.

A. COMBAT SYSTEM EFFECTIVENESS DOE

The combat system and sensors configurations selected as the payload in the three base models developed in Chapter II have weapons and sensors that fulfill the needs considered in the operational situations established by [2]. At the beginning of this work, it was stated that the operational capabilities to be considered are found in the work done by [2] and [3].

The DOE for combat system effectiveness considers the same three factors considered in the DOE of the ship synthesis model. The intention is to enable the connection between the ship synthesis model and combat-system effectiveness.

In this case, a custom design with eight points was selected. Figure 11 shows the DOE layout.

Table 11. Combat-systems effectiveness DOE.

	PAYLOAD WEIGHT	RANGE	SHP
1	350	4000	23500
2	350	5000	47000
3	270	4000	47000
4	270	4000	47000
5	350	5000	47000
6	270	5000	23500
7	270	5000	23500
8	350	4000	23500

For this DOE, a midpoint design was not considered because the base models built have payload weights of 350, 270, and 285 tons, and each configuration has systems and elements that provide anti-air warfare (AAW), anti-surface warfare (ASUW), and anti-submarine (ASW) capabilities to the designed ships.

Under the models developed by [2], the OMOE and the MOE of each operational situation (OPSIT) were calculated using the parameters of the actual elements of the combat systems. Figure 5 shows an example of the implementation of the model for an AAW OPSIT, given the actual data for a combat-systems configuration. The actual value of the MOE is the value corresponding to actual value in the contour-profile box.

The same process was repeated with each OPSIT for each of the combat-system configurations to develop the custom design DOE. MOE1 corresponds to an antisubmarine operational situation, MOE2 corresponds to an anti-air, MOE3 corresponds to an anti-surface, and OMOE is the weighted sum of individual MOEs. In this particular situation, all MOEs have been given equal weight in the formulation of the OMOE.

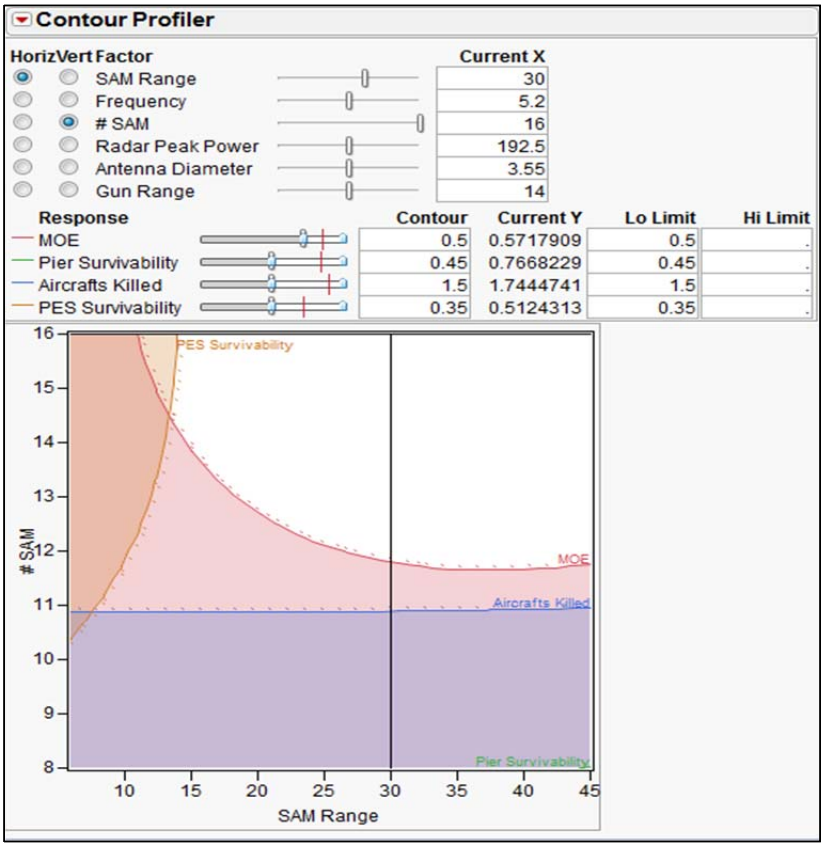

Figure 5. Determination of MOE example for AAW.

Table 12 shows the final values for the eight points of the DOE once all the data for the OPSIT models was collected.

Table 12. Combat-systems effectiveness DOE.

	PAYLOAD WEIGHT	RANGE	SHP	OMOE	MOE 1	MOE 2	MOE 4	DISPLACEMENT	MOE 3
1	350	4000	23500	0.645	0.59	0.79	0.3	2895	0.9
2	350	5000	47000	0.645	0.59	0.79	0.3	3125	0.9
3	270	4000	47000	0.53	0.49	0.4	0.3	2840	0.88
4	270	4000	47000	0.53	0.49	0.4	0.3	2840	0.88
5	350	5000	47000	0.645	0.59	0.79	0.3	3125	0.9
6	270	5000	23500	0.55	0.49	0.49	0.28	2540	0.88
7	270	5000	23500	0.55	0.49	0.49	0.28	2540	0.88
8	350	4000	23500	0.645	0.59	0.79	0.3	2895	0.9

B. COMBAT SYSTEM DOE RESULTS

The payload weight variable has the greatest impact in the response of the DOE. Figure 6 shows the Pareto plot, in which almost 90% of the response depends on payload weight, a reasonable result since the model is the simulation of combat-system effectiveness and payload weight is the set of all weapons and sensors in the configuration.

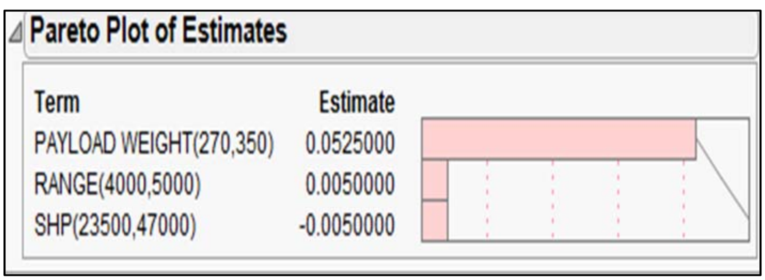

Figure 6. Combat-system effectiveness DOE Pareto plot.

Figure 7 is the prediction profiler. In it is also seen the strong influence of payload weight in the MOE responses, and it also shows the interaction of the other two factors and responses.

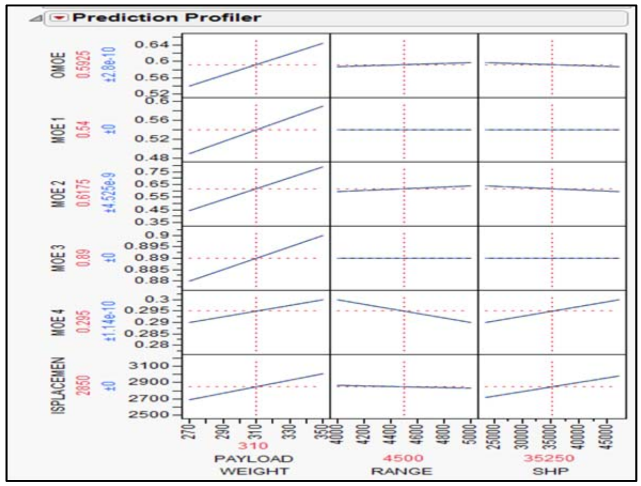

Figure 7. Combat-systems DOE prediction profiler.

C. INTERACTION AMONG THE MODELS

The methodology and tools developed in previous chapters shows us how RSM meta-models provide the opportunity for decision makers to conduct tradeoffs between requirements and how a ship design space can be represented in a graphical interactive form that makes it easier to understand the interplay among factors and responses.

To date, we have various separate meta-models from this and previous work. Each gives valuable information about predicting design performance as it pertains to combat system effectiveness while considering naval architectural aspects. Since the beginning of this research, an effort was made to link the combat-system effectiveness with the principal characteristics of naval architecture; with these two sets of information, we have a conceptual ship design that will be able to answer our design problem. Now the question is whether we can find ship designs that meet both responses simultaneously.

The relationship between combat system effectiveness and ship design synthesis is illustrated by using the contour plot of each one of the DOEs previously executed and explained. With these models, the factors (inputs) of the models are the same, so a direct comparison is possible.

It is important to note that the contour plots and all JMP graphical tools are interactive. This means that the response surface thresholds can be varied, and thus the contour plot will also change. Interactivity, which makes it possible to explore an infinite number of tradeoffs, consider a large number of possibilities in the design space, take less time to move through the design space, and provide a better understanding of factor relationships for the resolution of competing factors to arrive at the desired overall design effectiveness.

For interaction example one, the contour profiler has the same factors in the X and Y axes. In this example, the factors are payload weight and installed SHP. These factors were selected as having higher impact on the responses, especially with regard to payload weight. Next, responses limits were set. In a real case, these limits would result from a requirements analysis. Finally, the inputs are the factors of interest already chosen (payload weight and SHP, in this example) which are set to the same value in both models.

Figure 8 shows the contour plots generated for this example. It can be seen that the contour plot for the ship synthesis model, on the left, represents a point in the feasible region, while for the same factors, the contour profiler for combat system effectiveness model, on the right, represents a point design in the nonfeasible region. Thus, decision makers can evaluate if it will be convenient to maintain this specific ship design, and compromise the level of system combat effectiveness to move from then on feasible region to a feasible one, or if they would prefer to make ship characteristic compromises—varying the payload weight to make both models fall within a feasible region, for example, or making changes to the limits of the responses to expand or contract these regions.

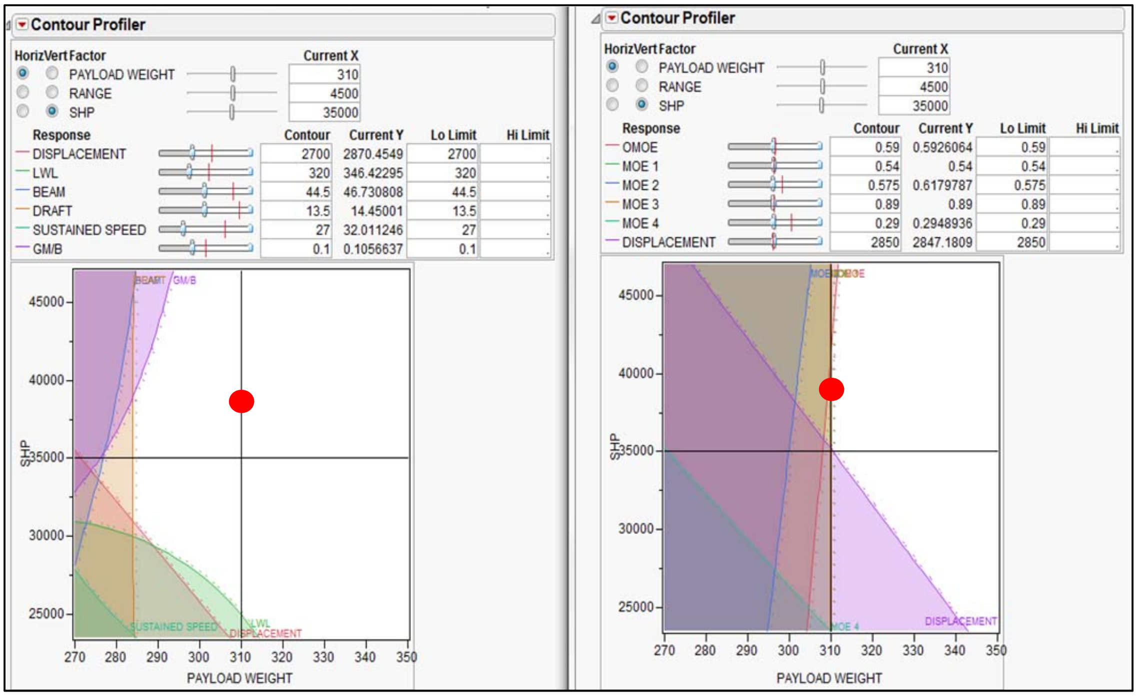

Figure 8. Contour plot for model interaction one.

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V. CONCLUSIONS AND RECOMMENDATIONS

A. SUMMARY

One of the projects of the Colombian navy in the medium- to long- term is the design and construction of combatant ships to replace the existing class of frigates of the type Almirante Padilla when they reach the end of their lifecycle. This project is being enacted at the Colombian shipyard, COTECMAR. Rapid technological trends, tight defense budgets, and shipyard inexperience in the construction of medium-tonnage surface ships make it necessary to employ new tools that allow the exploration of design spaces instead of relying on single ship concept point designs, in order to achieve the most effective design possible.

This work centered on developing a methodology that explicitly shows the interaction and impacts that different systems and operational capabilities have on overall ship design. A set of ship designs was created using a ship synthesis model. These designs characterize ships from a combat systems high end, lower limit, and midpoint of the design space, within which the Colombia navy can find a design that meets operational needs.

The base models were designed around varying typical payloads, including sensors, weapons, and ordnance, and some other important operational characteristics like range and installed SHP. The use of techniques like DOE and RSM, accessed through JMP software, based on statistical methods and interactive and graphical tools, allows the designer to explore the relationship between ship design factors and operational mission responses.

One of the most important tools in the proposed methodology is the JMP contour profiler. This tool can be used to explore the design space and enables interactive decision making, leading to a better understanding of the relationship between various factors and responses, identifying conflicting attributes, and performing tradeoffs among the ship design alternatives generated.

The other objective of this work is to establish a methodology that couples ship synthesis design and combat system effectiveness. For this objective, a new DOE was generated, in which the factors are based on variables for the ship synthesis DOE, and the responses are the MOE for each situational operation, and an overall OMOE that is the sum of weighted values of each MOE. Towards this objective, it was necessary to use the models designed by [2]. Once the DOE was performed, a direct comparison of contour profilers of the ship synthesis model RSM and of combat system effectiveness RSM became possible. An example of this process shows a ship design that may meet design requirements from the point of view of naval architecture, but not meet the requirements of combat system effectiveness. The contour profiler can then be used to allow decision makers to either adjust the ship parameters to meet the desired OMOE, or to compromise the levels of mission related MOE to achieve a balanced and feasible outcome.

This tool is an interactive and graphical way to conduct tradeoffs, establish factors, understand response relationships, allocate more effort and resources on key parameters of the design, and facilitate better top level decision making.

B. CONCLUSIONS

The original objective of this work, namely to demonstrate a basic methodology for early stage conceptual design of a combatant ship, has been achieved through a combination of a ship synthesis model, the use of Design of Experiments, and Response Surface Methodologies techniques. This combination allows us to determine and explore the design space in which an optimal solution lies. These techniques simplify the analysis of data and allow us to identify the relationships among the different factors involved in ship design.

The contour profiler plot is a graphical and interactive tool to identify regions of feasible and non-feasible design. One of the main advantages of this tool is the possibility of changing the values of factor limits in order to conduct tradeoff analysis, establish the relationship between factors, gain a better understanding of the system, identify conflicting requirements, and allocate more efforts and resources to be applied to key parameters that have the greatest impact on the ship design.

The use of RSM meta-models makes it possible to establish the relationship between operational capabilities and the basic parameters of naval architecture. They are useful for better-informed decision making between naval architects and operational decision makers.

The link between combat systems-related mission effectiveness and naval architecture was demonstrated. The use of this technique prevents designs that meet operational requirements from being considered when they do not accomplish mission effectiveness desires (or vice versa), thus yielding a solution that really meets stakeholder needs.

C. RECOMMENDATIONS

The following areas bear further investigation to improve understanding and gain experience and fidelity in the development of the design tool proposed and evaluated in this project.

- Develop cost models for all systems studied, since cost is a key factor. It will be useful to establish a good method to predict cost and conduct cost-effectiveness tradeoff studies.
- Develop new operational situations (OPSITS) that represent more detailed mission scenarios of interest to allow decision makers to identify more systems or equipment in order to enhance the ability to for the ship design to participate in mission effectiveness studies. This would increase the fidelity of the operational capability assessments for the ship and would give more flexibility in the use of naval power.
- Improve the models for determining the MOE, since they determine the type of combat systems and sensor to be used. These elements are the key point in the development of the DOE.

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